INFLUENCE OF INERTIA MOMENTUM OF CYLINDER ON POWER CONSUMPTION DURING CORN EAR THRESHING

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Abstract. Experimental research was performed in 2010-2012 at the testing ground of the Department of Agricultural Machinery using the stationary single-cylinder tangential threshing unit with additional ballast bars being attached in the gaps between rasp bars of the threshing cylinder in order to vary the moment of inertia of the cylinder from 8.34 kg·m^2 to 15.73 kg·m^2. The operating parts of the stationary threshing unit were rotated by a 15 kW electric motor. The active power required for rotation of the threshing cylinder was measured using the electric power system analysis devices *Metrel* MI2492 and *Almemo 2890-9*. Rotation of the threshing cylinder with no load requires 4.6 ± 0.1 kW, and of the back beater – approximately 0.6 kW of power. The power consumption for rotation of no-load cylinder remained almost constant by increasing a moment of inertia from I = 8.34 kg·m^2 (cylinder mass m = 204.2 kg) to I = 15.73 kg·m^2 (m = 320.2 kg). The experimental research of corn ear threshing showed that increase in the corn feed rate from 4 kg·s^{-1} to 12 kg·s^{-1}, results in increase in the amount of the power required for threshing from 8.1 kW to 18.7 kW (I = 8.34 kg·m^2) and from 7.6 kW to 17.5 kW (I = 15.73 kg·m^2), respectively. In the result of the research of the power consumption during corn ear threshing, the effect of increased moment of inertia of the threshing cylinder on the course of the threshing process was found to be positive. Moreover, operation of the threshing cylinder with a moment of inertia of 15.73 kg·m^2 at inconsistent corn feed rate was found to be the most stable.

Keywords: combine harvester, corn, inertia momentum, threshing cylinder, feed rate.

Introduction

Any combine harvester is a complicated dynamic system encompassing many interdependent input and output variables. One of the major input parameters, that is considered to directly determine the quality of a combine harvester operation, is the consistent feed rate of the crop flow [1; 2]. The research findings show, however, the feed rate of crop inflow into a combine harvester to be inconsistent during harvesting. This, in turn, determines reduction in the speed and kinetic energy of the threshing cylinder, leading to decreased overall threshing performance. This can result in significantly slower grain separation through the grate-bar of the concave and increased threshing loss [3]. One of the means for effective threshing of corn ears at inconsistent feed rate, while avoiding significant reduction in the cylinder speed and increase in cylinder loss, is increase in the moment of inertia of the threshing cylinder [4].

Theoretical studies show that increase in the moment of inertia of the threshing cylinder leaves the numerical value of the critical angular velocity ω_{cr} constant, whereas acceleration of the cylinder necessary for crop threshing is reduced [4]. The threshing cylinder of greater mass or moment of inertia can operate at higher feed rate. The moment of inertia of the threshing cylinder is dependent on the power of the motor.

It has been proved that under linear increase in a load of the threshing cylinder, the speed of the cylinder with higher moment of inertia decreases at slower pace. Under the cyclically pulsating load, the pattern of the change in angular velocity of the threshing cylinder is similar to the change in load. However, as the amplitude of the change in speed of rotation of the higher-mass threshing cylinder is smaller, the process of threshing happens to be more consistent [2].

It is commonly suggested that 84 % of the power of grain combine harvester is normally consumed by its operating mechanisms (threshing cylinder accounts for 31 %; back beater – 16 %; cutting table and feeder house – 21 %; drive line – 16 %; grain augers and elevators – 8 %; cleaning shoe – 6 %, and straw walker – 2 %) [5]. Depending on specific harvesting conditions, threshing uses 0.3-1.5 kW per second for each kilogram of corn ears fed into the threshing apparatus [6]. The power used for threshing is mainly comprised of three constituents: for impacts of the rasp bar to the flow of crops, for crop compression and for crop transportation over the surface of the concave [7]. Consumption of both power as well as fuel of the combine harvester is mainly dependent on the flow of the crops fed into the combine harvester which is directly related to the combine harvester ground speed [8].

The research goal is to find out the effect of the moment of inertia of the threshing cylinder of a combine harvester on the power consumption of the threshing apparatus.

Materials and methods

The experimental research was performed in 2010-2012 in the testing ground at the Department of Agricultural Machinery using the stationary tangential threshing unit (Fig. 1). The stationary threshing unit was comprised of the corn ear belt-feeder (1) with 10 m in length and 1.2 m in width; the tangential threshing cylinder with 8 rasp bars (3) with the diameter of 0.6 m and width of 1.2 m, which was enveloped by the grate-bar type concave (4) at the angle of 146º; the back-beater (6) and the transition grate (7).

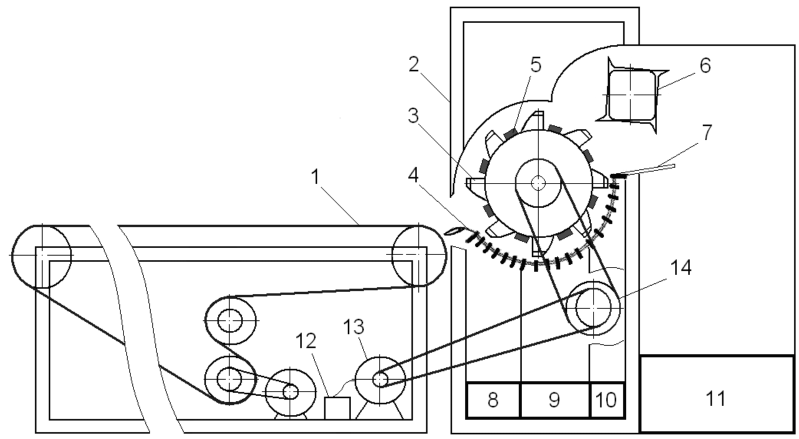

Fig. 1. **Scheme of the stationary corn ear threshing unit:** 1 – corn ear belt-feeder; 2 – frame of the threshing unit; 3 – threshing cylinder; 4 – concave; 5 – additional ballast bars; 6 – back beater; 7 – transition grate; 8, 9, 10 – tanks for collecting grain; 11 – collection tank; 12 – devices for measuring electric current, voltage and power; 13 – electric motor; 14 – variator

At opposite sides of the threshing cylinder, in the gaps between the rasp bars eight ballast bars of 14.5 kg each have been attached using bolts with the aim to increase the weight of the threshing cylinder leading to increased moment of inertia. Total mass of the rotating parts including the threshing cylinder shaft, with ballast bars excluded, amounted for 204.2 kg; out of which 40.0 kg accounted for the cylinder shaft, 85.0 kg – threshing cylinder, 48.0 kg – variator pulley, and 31.2 kg – 8 rasp bars. In this particular case, the moment of inertia amounted for 8.34 $kg \cdot m^2$. In the result of attaching 8 additional ballast bars, the moment of inertia increased to 15.73 $kg \cdot m^2$. The above-indicated numerical values of the moments of inertia have been found using computer software *Solid Edge* [9].

The operating parts of the stationary threshing unit were rotated by a 15 kW electric motor. The cylinder speed was adjusted in the range of 450 min^{-1} by the variator the rotation velocity of which was measured using a digital infrared tachometer Chauvin® Arnoux C.A 1727. The measurement range of the device was 100 ÷ 1000 min^{-1}, and measurement error was $\pm 1 \cdot 10^{-4}$ of the measured value.

Rotation of the threshing cylinder requires for the active power which was measured using the electric power system analysis device ME-MI2492 (*Metrel*). The measurement range of the device was 0-150 kW, value of the scale-interval – 0.1 kW, and power measurement error was ± 3 % of the measured value. Afterwards, the total power consumption for threshing corn ears has been found. The amount of the power necessary for corn ear threshing was found by deducting the amount of the power required for rotation of no-load threshing cylinder from the total power consumption. Simultaneously with *Metrel* device, measurements of the current and voltage necessary for rotation of the electric motor were performed using *Almemo 2890-9* device. Knowing these data made verifying calculations of power consumption possible.

The amount of the power consumed from the power supply system can be calculated from the following equation:

$$N_{el} = 3U_f I_f \cos\varphi \text{, W} \tag{1}$$

where U_f – phase voltage, V;
I_f – phase current, A;
$\cos\varphi$ – coefficient of the electric motor ($\cos\varphi = 0.82$).

The power required for rotation of the threshing apparatus is lower than that calculated from Equation 1, because some power is lost at the belt drive and bearings. The coefficient of efficiency of the electric motor АИР-160M6 (15 kW) amounts for 0.89, that of three belt drives that rotate the operating parts of the threshing apparatus – 0.88, that of six ball bearings – 0.97. Consequently, it can be assumed that rotation of the operating part of the threshing apparatus accounts for 76 % of the power consumed from the power supply system. Referring to these assumptions, the power measured using *Metrel* device and that calculated by Equation 1 were not different.

First, when conducting the research, power requirement for rotation of the threshing cylinder with no load was calculated at cylinder speed 450 min^{-1} set by the variator. Analogous measurements were made while feeding corn ears at different rate of 4 $kg \cdot s^{-1}$ to 14 $kg \cdot s^{-1}$ into the threshing apparatus. This way the amount of the power required for corn threshing was found. For the purpose of research the corn ears of variety *Pioneer* PR39D60 in the phase of full maturity with the moisture content of 26.5 ± 0.3 % were threshed in the stationary threshing apparatus.

For the purpose of finding the effect of a moment of inertia of the threshing cylinder on the power consumption at constant feed rate of the flow, corn ears were evenly distributed on the conveyor belt of 5 m in length, and fed into the tangential threshing apparatus at the speed of 1.0 $m \cdot s^{-1}$. The gap between the rasp bar of the threshing cylinder and the concave bar at the inlet was 38 mm, and that at the outlet – 32 mm.

For the purpose of simulation of the variable load of the threshing apparatus, 3 m of the conveyor belt were covered with the 18 kg sample of evenly distributed corn ears, in order to ensure their inflow at the feed rate of 6 $kg \cdot s^{-1}$ into the threshing apparatus, then the next 3 m of the conveyor belt were covered with the 36 kg sample of evenly distributed corn ears, and afterwards another 3 m of the conveyor belt – with the 18 kg sample, again. Arranged in this pattern, corn ears were fed into the threshing apparatus at the speed of 1.0 $m \cdot s^{-1}$. Following this pattern, for the first 3 seconds corn ears were fed into the threshing apparatus at the rate of 6 $kg \cdot s^{-1}$, then for the next 3 seconds – at the rate of 12 $kg \cdot s^{-1}$, and for the last 3 seconds – at the rate of 6 $kg \cdot s^{-1}$ again.

Each experiment was repeated 3 times. Research findings were assessed using the methods of dispersion and correlation-regression analysis. Mean values, their standard deviations and confidence intervals with probability level of 0.95 were found.

Results and discussion

Effect of the consistent corn feed rate on the power consumption. It was found that rotation of the back beater alone required for approximately 0.6 kW of power. Rotation of the threshing cylinder with no load (including the back beater) required 5.2 ± 0.2 kW of power. When the preset cylinder speed was reached, further rotation of the heavier threshing cylinder (m = 320.2 kg, I = 15.73 $kg \cdot m^2$) required power in so far as when compared to the threshing cylinder with mass of 204.2 kg (I = 8.34 $kg \cdot m^2$). However, the time required for racing of the heavier threshing cylinder was by 0.5 s longer.

The experimental research of threshing showed that increase in the corn feed rate from 4 $kg \cdot s^{-1}$ to 12 $kg \cdot s^{-1}$, results in increase in the amount of average power required for threshing corn ears from 8.1 kW to 18.7 kW (I = 8.34 $kg \cdot m^2$) and from 7.6 kW to 17.5 kW (I = 15.73 $kg \cdot m^2$), respectively (Fig. 2 and 3). According to the research findings, it was observed that higher moment of inertia of the threshing cylinder leads to more stable power consumption during the threshing process and the amplitude of its variation is smaller, meaning that the process of threshing is more consistent.

The power required for threshing N_{thresh} is found by deducting the amount of the power required for rotation of no-load threshing cylinder, which is equal to 5.2 ± 0.2 kW, from the average total power consumption *N*. In the result of the research it was observed that in operation of the threshing cylinder with lower moment of inertia, higher peak power consumptions are achieved (Fig. 2 and 3). This was found through analysis of maximum power consumption during the process of threshing. Moreover, when the average total power consumption *N* and power required for threshing N_{thresh}, while increasing the feed rate of corn ears from 4 kg·s^{-1} to 12 kg·s^{-1}, is linearly increasing, the increase in peak power consumptions is found to be more rapid – they vary exponentially. These peaks of power required determine the consistency of the threshing process. Consequently, the conclusion can be made regarding the positive influence of the increased moment of inertia on the process of threshing. This suggestion was further proved true by experimental investigations of threshing duration. Recording of the threshing process using a high-speed camera showed that the process of threshing was more rapid when corn ears were threshed by the threshing cylinder with increased moment of inertia to 15.73 kg·m^2 when compared to more light-weight threshing cylinder. It is especially the case at the feed rate above 10 kg·s^{-1} of corn ears.

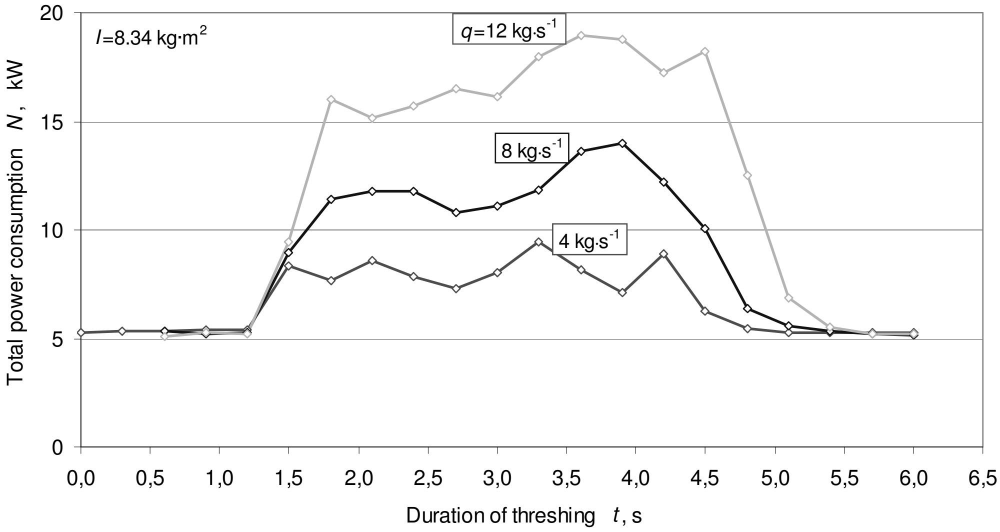

Fig. 2. **Variation of power consumption under different corn feed rate with the moment of inertia of the threshing cylinder I = 8.34 kg·m^2 (cylinder mass m = 204.2 kg)**

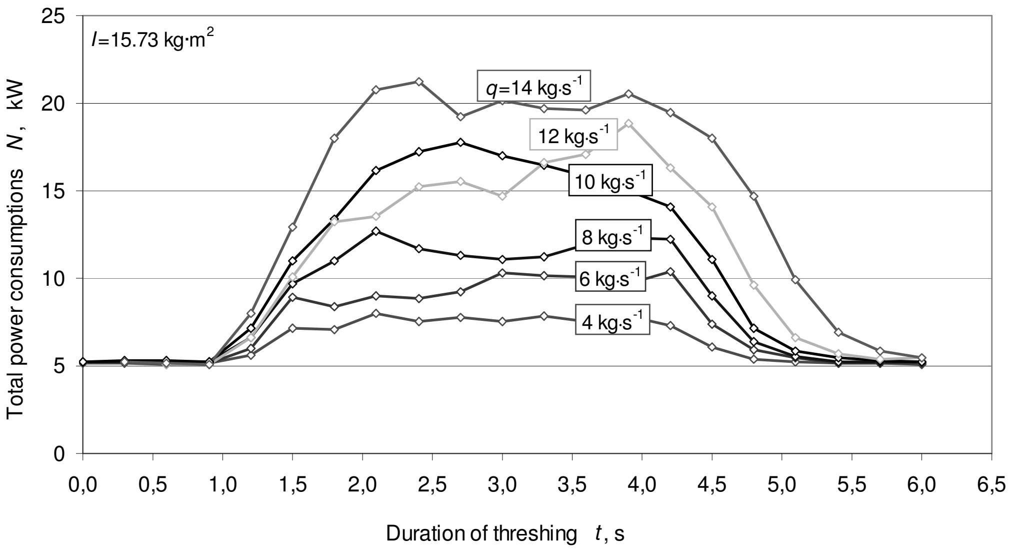

Fig. 3. **Variation of power consumption under different corn feed rate with the moment of inertia of the threshing cylinder I = 15.73 kg·m^2 (cylinder mass m = 320.2 kg)**

The effectiveness of the threshing process can be evaluated by calculating the amount of power required for threshing one kg·s^{-1} of corn ears. The lower the value obtained, the more effective operation of the threshing apparatus is. In the result of the research it was found that after the feed rate of corn ear inflow into the threshing apparatus was increased from 4 kg·s^{-1} to 12 kg·s^{-1}, the total amount of power required for threshing one kg·s^{-1} of corns in the threshing apparatus decreased from 2.00 kW to 1.52 kW (I = 8.34 kg·m^2) and from 1.89 kW to 1.45 kW (I = 15.73 kg·m^2), respectively (Fig. 4). When assessing the useful power, i.e., the amount consumed for the threshing process, less significant decrease in the power consumption was observed. Based on the obtained research findings on power consumption, the conclusion can be made that the threshing apparatus with the cylinder of 1.2 m in length, 0.6 m in diameter and having 8 rasp bars, is supposed to operate effectively under the feed rate of at least 8 kg·s^{-1} of corn ears. In case of lower feed rate more than 50 % of power is used for rotation of the operating parts of no-load threshing cylinder alone, i.e., for doing useless work (Fig. 5).

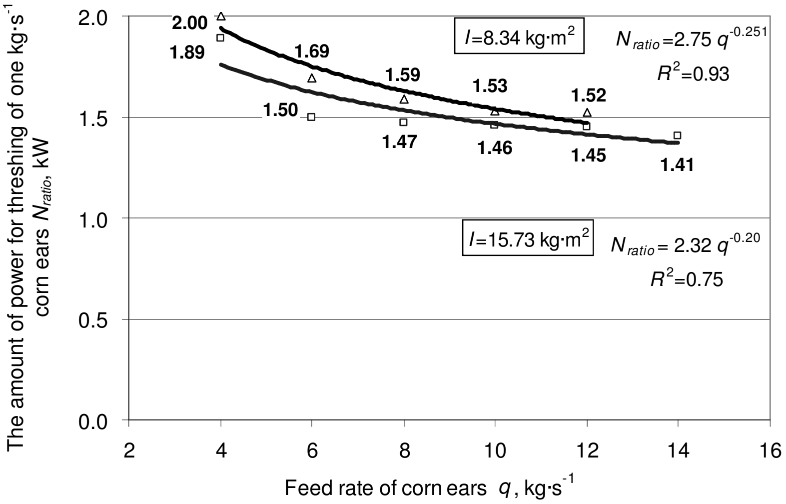

Fig. 4. **Effect of the feed rate *q* on the amount of power required for threshing of one kg·s^{-1} of corn ears N_{ratio} while operating threshing cylinders with different moments of inertia *I***

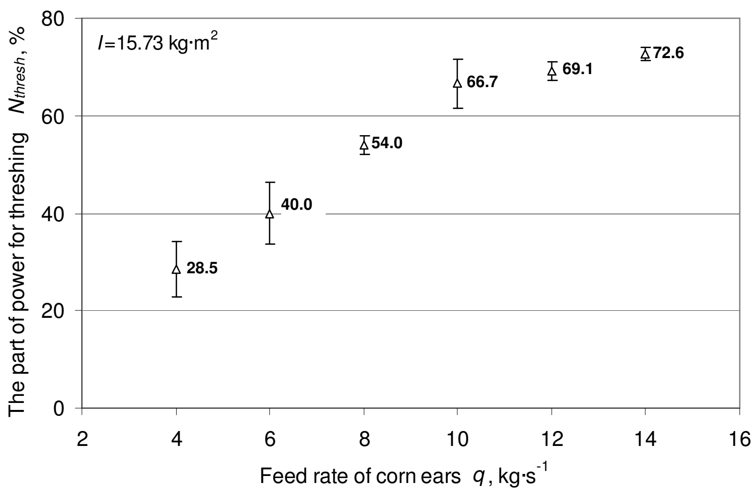

Fig. 5. **Effect of the corn feed rate on the part of power required for only threshing corn ears (I = 15.73 kg·m^2, cylinder mass m = 320.2 kg)**

Effect of the moment of inertia of the threshing cylinder on power consumption at inconsistent feed rate of corn ears. The variation in power consumption during threshing at inconsistent feed rate of corn ears into the threshing apparatus has been observed (Fig. 6). Feeding of corn ears into the threshing apparatus was divided into three following stages. During the research, the threshing apparatus was fed with corn ears at the feed rate of 6 kg·s^{-1}, 12 kg·s^{-1}, and 6 kg·s^{-1} with intervals of 3 s. The research findings showed that the flow of corn ears fed at the rate of 6 kg·s^{-1} was threshed in 3 s, whereas threshing at feed rate of 12 kg·s^{-1} required for 0.5 s longer period. In Stage 3, when the threshing apparatus was fed with the same flow of corn ears as in Stage 1, the average power consumption was by approximately 20 % higher.

In the result of the research in the power consumption during corn ear threshing at inconsistent feed rate, the effect of increased moment of inertia of the threshing cylinder on the course of the threshing process was found to be positive. The total power consumption for threshing following increase of the moment of inertia of the threshing cylinder from 8.34 kg·m^2 to 15.73 kg·m^2 remained almost constant in the threshing stages 1 and 3 (Fig. 6). Only in Stage 2, when threshing corn ears in the threshing cylinder with the higher moment of inertia (15.73 kg·m^2), lower power consumption was recorded when compared to more light-weight threshing cylinder. Moreover, the operation of the threshing cylinder with the moment of inertia of 15.73 kg·m^2 was found to be the most stable.

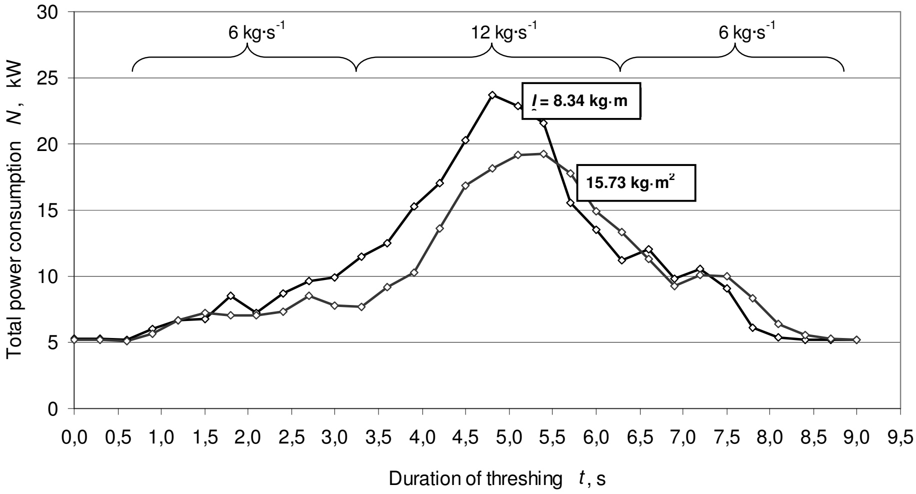

Fig. 6. **Variation of power consumption during corn ear threshing at inconsistent feed rate, when operating cylinders with different moments of inertia**

Conclusions

1. Rotation of no-load threshing cylinder requires 4.6 ± 0.1 kW, and of the back beater – approximately 0.6 kW of power. Power consumption for rotation of no-load cylinder remained almost constant by increasing in the moment of inertia from I = 8.34 kg·m^2 (cylinder mass m = 204.2 kg) to I = 15.73 kg·m^2 (m = 320.2 kg), but the racing time of the cylinder increased by approximately 0.5 s.
2. The experimental research in corn threshing showed that increase in the corn feed rate from 4 kg·s^{-1} to 12 kg·s^{-1}, results in increase in the amount of the power required for threshing corn ears from 8.1 kW to 18.7 kW (I = 8.34 kg·m^2) and from 7.6 kW to 17.5 kW (I = 15.73 kg·m^2), respectively. In the result of the research of the power consumption during corn ear threshing, the effect of increased moment of inertia of the threshing cylinder on the course of the threshing process was found to be positive. Moreover, operation of the threshing cylinder with the moment of inertia of 15.73 kg·m^2 at inconsistent corn feed rate was found to be the most stable.

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